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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER	2. GOVT ACCESSION NO. AD-A128 741	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) Demonstration and Analysis of an Improved Nondestructive Evaluation (NDE) Method for Rotary Wing Head Spindle Threads		5. TYPE OF REPORT & PERIOD COVERED Final Report
		6. PERFORMING ORG. REPORT NUMBER SwRI 15-5607-809
7. AUTHOR(s) Gary L. Burkhardt, Cecil M. Teller		8. CONTRACT OR GRANT NUMBER(s) DLA900-79-C-1266
9. PERFORMING ORGANIZATION NAME AND ADDRESSES Southwest Research Institute, P.O. Drawer 28510, San Antonio, TX 78284		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS U.S. Army Aviation Research and Development Command, St. Louis, MO 63120		12. REPORT DATE June 1982
		13. NUMBER OF PAGES 24
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

MAY 3 1 1983

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

helicopters
nondestructive testing
electric current perturbation
fatigue cracks

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Present inspection methods for the Black Hawk helicopter rotary wing head spindle require almost complete disassembly of the rotary wing head and hub assemblies to expose the failure critical threads for inspection. Even with direct access to the threads, detection of fatigue cracks in the thread roots is very difficult using penetrant and visual methods. Therefore, the primary purpose of this project was to demonstrate an improved nondestructive evaluation (NDE) method for the spindle using the electric current perturbation (ECP) method which requires only minimal disassembly for safety-of-flight

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inspections. High sensitivity inspection of the spindle threads applicable to routine teardown maintenance was also demonstrated.

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30 June 1982

Mr. Windel M. Baker
USAAVRADCOM, DRDAV-QE
3300 Goodfellow Blvd.
St. Louis, MO 63120

Subject: Final Report, Contract No. DLA900-79-C-1266, SwRI Project 15-5607-809, "Demonstration and Analysis of an Improved Nondestructive Evaluation (NDE) Method for Rotary Wing-Head Spindle Threads"

Dear Mr. Baker:

This letter and attachment comprise the Final Report on an evaluation of the electric current perturbation (ECP) method for fatigue crack detection in the threaded section of the Black Hawk helicopter rotary wing-head spindle. The attachment contains details of the project, along with conceptual designs for inspection system hardware. We are convinced that the results using this advanced NDE method provide the basis for recommending prototype equipment development.

Two ECP spindle inspection systems are recommended. One system would be used at the depot level with the spindle removed from the helicopter for detection of very small fatigue cracks which could possibly be removed by blending, allowing the spindle to be returned to service. A budgetary estimate for this system is $150,000. The second system would be portable and would be used with the spindle in place on the helicopter for safety-of-flight inspection. Use of this system would require that the rotary wing be removed or rotated aside on one attaching pin to provide access to the spindle bore. A budgetary estimate for this system is $140,000. Some cost savings could be realized by building both systems. A delivery time of six months is anticipated.

We would be pleased to provide a detailed briefing at your organization regarding the results of this project and the concepts for prototype inspection equipment and look forward to continuing work with you on this very important problem. If you have any questions, please do not hesitate to call me at (512) 684-5111, extension 2730.

Very truly yours,

for

John R. Barton, Vice President
Instrumentation Research Division

Prepared by:

Gary L. Burkhardt
Sr. Research Scientist

Cecil M. Teller, Ph.D.
Manager, NDE Research

Enclosure

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WITH OFFICES IN HOUSTON, TEXAS, AND WASHINGTON, D.C.

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DEMONSTRATION AND ANALYSIS OF AN IMPROVED NONDESTRUCTIVE EVALUATION (NDE) METHOD FOR ROTARY WING HEAD SPINDLE THREADS

By

Gary L. Burkhardt

Cecil M. Teller

Prepared for

U.S. Army Aviation Research and
Development Command
St. Louis, Missouri

Contract DLA900-79-C-1266

SwRI Project 15-5607-809

June 1982

SAN ANTONIO, TEXAS
WITH OFFICES IN HOUSTON, TEXAS, AND WASHINGTON, D.C.

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I. INTRODUCTION AND SUMMARY

Present inspection methods for the Black Hawk helicopter rotary wing head spindle require almost complete disassembly of the rotary wing head and hub assemblies to expose the failure critical threads for inspection. Even with direct access to the threads, detection of fatigue cracks in the thread roots is very difficult using penetrant and visual methods. Therefore, the primary purpose of this project was to demonstrate an improved nondestructive evaluation (NDE) method for the spindle using the electric current perturbation (ECP) method which requires only minimal disassembly for safety-of-flight inspections. High sensitivity inspection of the spindle threads applicable to routine teardown maintenance was also demonstrated.

The ECP method consists of establishing a current flow in the material to be inspected and then measuring current perturbations caused by nonconducting defects such as cracks.(1) Usually, the current flow is established by a noncontacting induction coil and the current perturbations are detected by a separate sensor which detects the magnetic field perturbation associated with the electric current perturbations.

Prior research under Air Force(2) and internal sponsorship(3) has documented the high sensitivity of the ECP method to both fatigue cracks and machined slots used to simulate the cracks. Demonstration projects also funded by the Air Force have shown detection of very small surface fatigue cracks in gas turbine engine disks(4) and second layer defects in relatively thick structural wing sections.(5) Based on known relationships obtained between peak ECP signal amplitude and the interfacial area for surface fatigue cracks and slots, it has been shown that even a tightly closed fatigue crack can be modeled by a machined slot of finite opening for the purposes of ECP evaluations. This equivalence in ECP response between slots and fatigue cracks is discussed further in Section III.C.

Since the ECP method has previously been applied to detection of small surface cracks, as well as to detection of subsurface and back surface cracks in relatively thick materials, it was applied to inspection of the spindle thread roots not only by scanning a probe on the crest of the threads, but also by scanning a probe in the spindle bore under the threads and inspecting through the wall thickness. The first configuration with the probe located on the crest of the threads is highly sensitive for detection of very small defects in the thread roots, although it requires removal of the spindle from the helicopter and removal of the spindle nut. With this arrangement, thumbnail shaped EDM slots as small as 0.021 in. long x 0.009 in. deep x 0.0025 in. wide were detected. The second configuration requires that only the rotary wing be removed or swung aside with one attachment pin removed so that a probe can be inserted into the spindle bore. Since this inspection is performed through the spindle wall, sensitivity is reduced due to the greater depth of penetration of the electromagnetic field and only larger defects are detectable. With this arrangement, detection of a thumbnail shaped EDM slot measuring 0.305 in. long x 0.087 in. deep x 0.004 in. wide was sucessfully demonstrated.

Details of the experimental procedures, results, conceptual designs for two types of inspection systems, conclusions and recommendations of this work are presented in the following sections.

II. EXPERIMENTAL ARRANGEMENT

A. Specimens

Two Black Hawk helicopter rotary wing head spindles were provided by the Army for use in this program. Figure 1 is a photograph of a spindle mounted in the laboratory scanning apparatus which is described below. The threaded region to the left of the figure is the area inspected with the ECP method. The thread specification is 2.500-12 UNJ-3A. In this report, the threads are numbered beginning at the splines, i.e. the first thread from the splines is thread no. 1.

Slots were machined in both spindles to simulate fatigue cracks. For initial tests with the ECP probe on the crest of the threads, rectangular air abrasive slots were machined into a thread root in Spindle No. 1 as shown in Figure 2. For initial tests with the ECP probe in the spindle bore, a thumbnail shaped slot was machined in one thread root using an abrasive wheel. To more closely simulate a fatigue crack geometry, thumbnail shaped EDM slots were later machined in the thread roots of spindle No. 2 as shown in Figure 3.

B. Laboratory Scanning Apparatus

A laboratory setup was made which allowed the spindle to be simultaneously rotated and translated axially by means of a motor drive and lead screw arrangement. Both ECP probe arrangements (on the crest of threads and in the bore) remained stationary and the relative motion between the probe and spindle provided a helical scan so that the probe maintained a fixed relationship with respect to the threads. This arrangement minimized influence of the thread geometry on the overall signal response. Rotational speed was 5.26 rpm.

C. ECP Probe on Crest of Threads

An ECP probe which utilizes a noncontacting induction method for establishing current flow and for sensing current perturbations associated with defects was configured to ride on the crest of the threads. This probe provides current flow perpendicular to the thread at a frequency of 100 KHz which provides optimum detection of small fatigue cracks which grow along the thread root. The probe is shown in place on the threaded region of the spindle in Figure 4.

Analog ECP signals were digitized as a function of probe position using a Nicolet model 2090-III digital oscilloscope and were transferred to a Tektronix 4052 computer for signal processing and plotting. To provide enhancement of the flaw signals, a digital high-pass filter was used to reject the lower frequency signal components not associated with defects. The digital filter was used for convenience in this investigation; an analog filter could be used in inspection hardware.

D. ECP Probe in Spindle Bore

A second arrangement was established utilizing an ECP probe positioned in the spindle bore to provide defect detection through the spindle wall thickness. The probe comprises an elongated induction coil to provide

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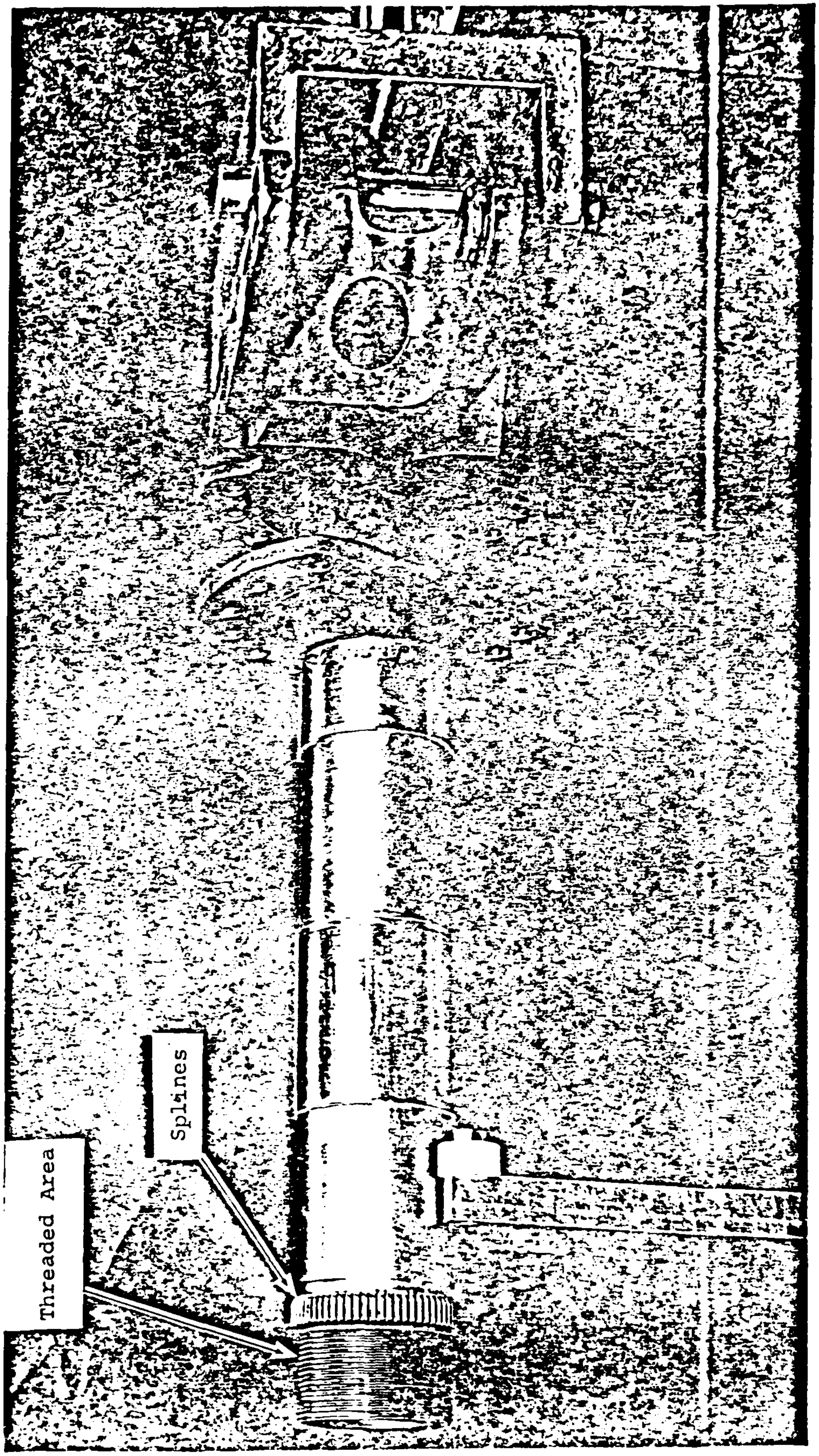
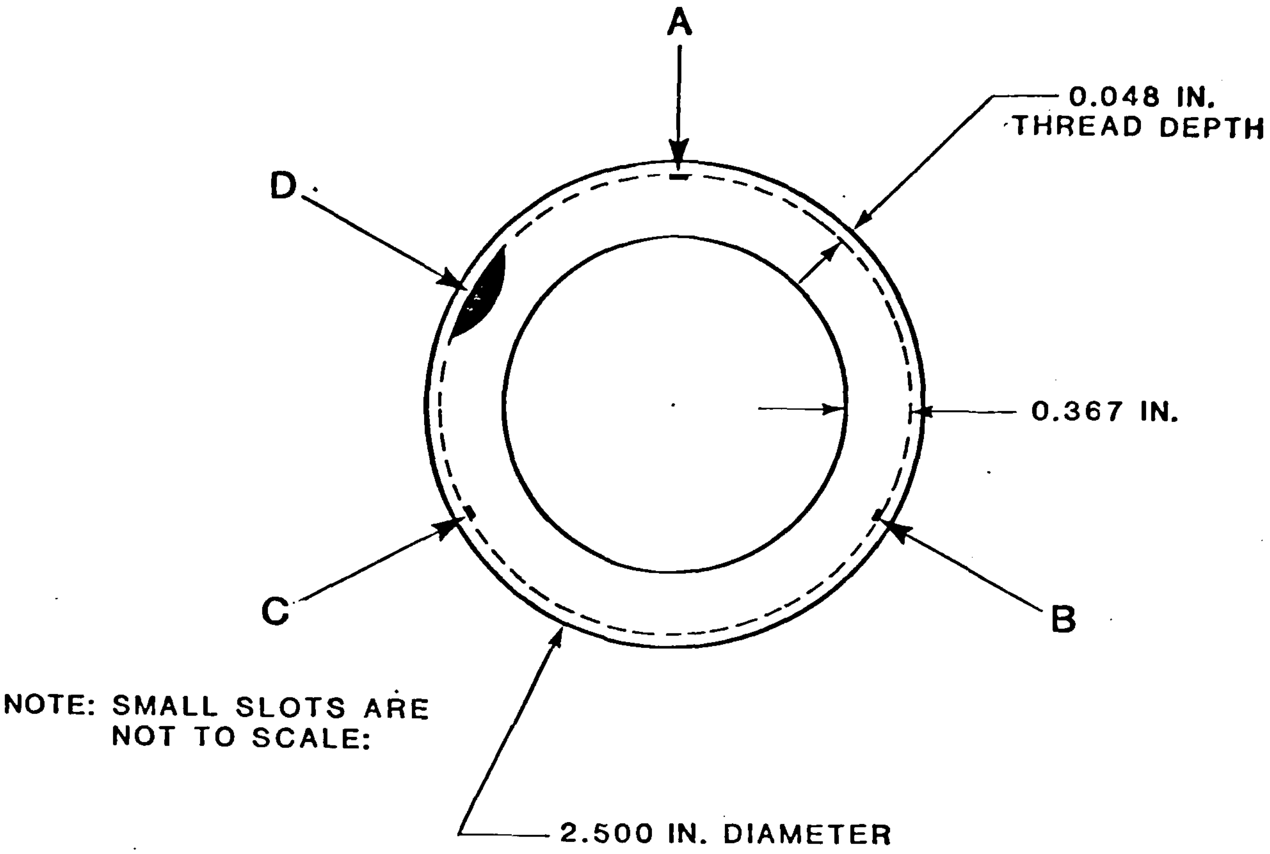


FIGURE 1. BLACK HAWK ROTARY WING HEAD SPINDLE IN LABORATORY SCANNING APPARATUS



Defect	Length (in.)	Depth (in.)	Width (in.)	Shape	Type	Thread No. (From Spline
A	0.106	0.014	0.008	Rectangular	Air Abrasive	11
B	0.068	0.010	0.007	Rectangular	Air Abrasive	11
C	0.025	0.017	0.007	Rectangular	Air Abrasive	11
D	0.600	0.110	0.022	Thumbnail	Abrasive Wheel	4

FIGURE 2. SIMULATED CRACKS IN SPINDLE NO. 1

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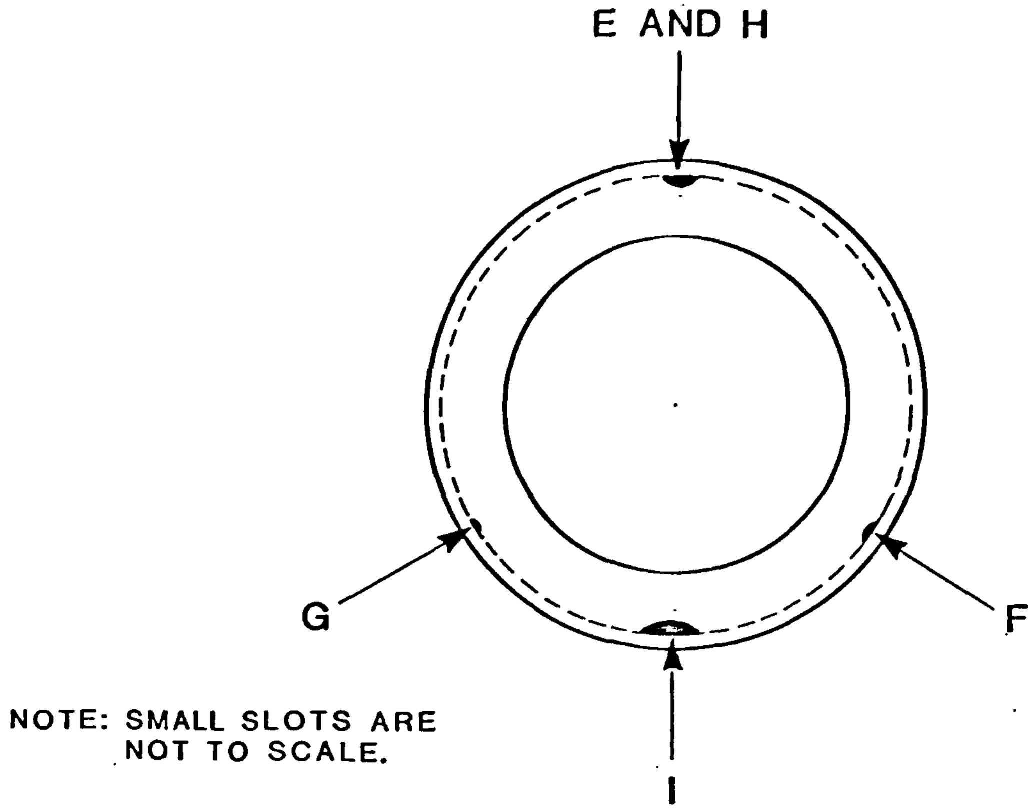


Defect	Length (in.)	Depth (in.)	Width (in.)	Shape	Type	Thread No. (From Spline)
E	0.052	0.014	0.0029	Thumbnail	EDM	10
F	0.039	0.010	0.0026	Thumbnail	EDM	10
G	0.021	0.009	0.0025	Thumbnail	EDM	10
H	0.195	0.060	0.0025	Thumbnail	EDM	1
I	0.305	0.087	0.004	Thumbnail	EDM	1

FIGURE 3. SIMULATED CRACKS IN SPINDLE NO. 2

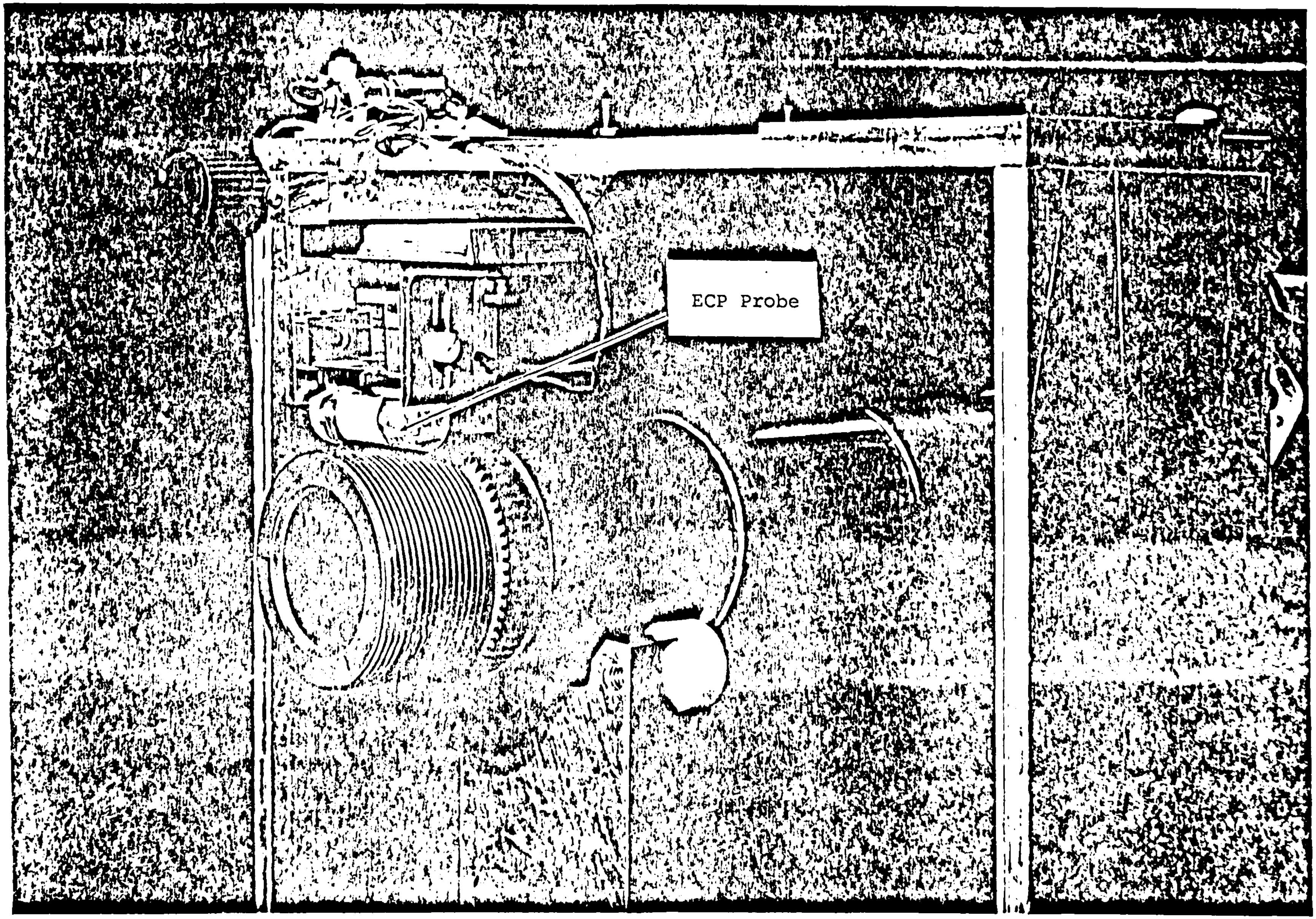


FIGURE 4. ECP PROBE ON CREST OF THREADS

current flow perpendicular to the direction of the threads for optimum defect detection and a separate sensor for detection of current flow perturbations associated with defects. Several sensor configurations were investigated to obtain optimum defect response. The probe is shown positioned in the spindle bore in Figure 5. A portion of the induction coil is visible; the sensor is located further inside the bore. This probe was energized at a frequency of 5 KHz which provided a skin depth equal to the spindle wall thickness of 0.367 in. Note that the spindle nut was left in place to simulate a spindle installed on a helicopter.

ECP data were acquired using the same instrumentation arrangement described previously. The digital high-pass filter was used to remove the signal gradient obtained as the scan approaches the end of the spindle.

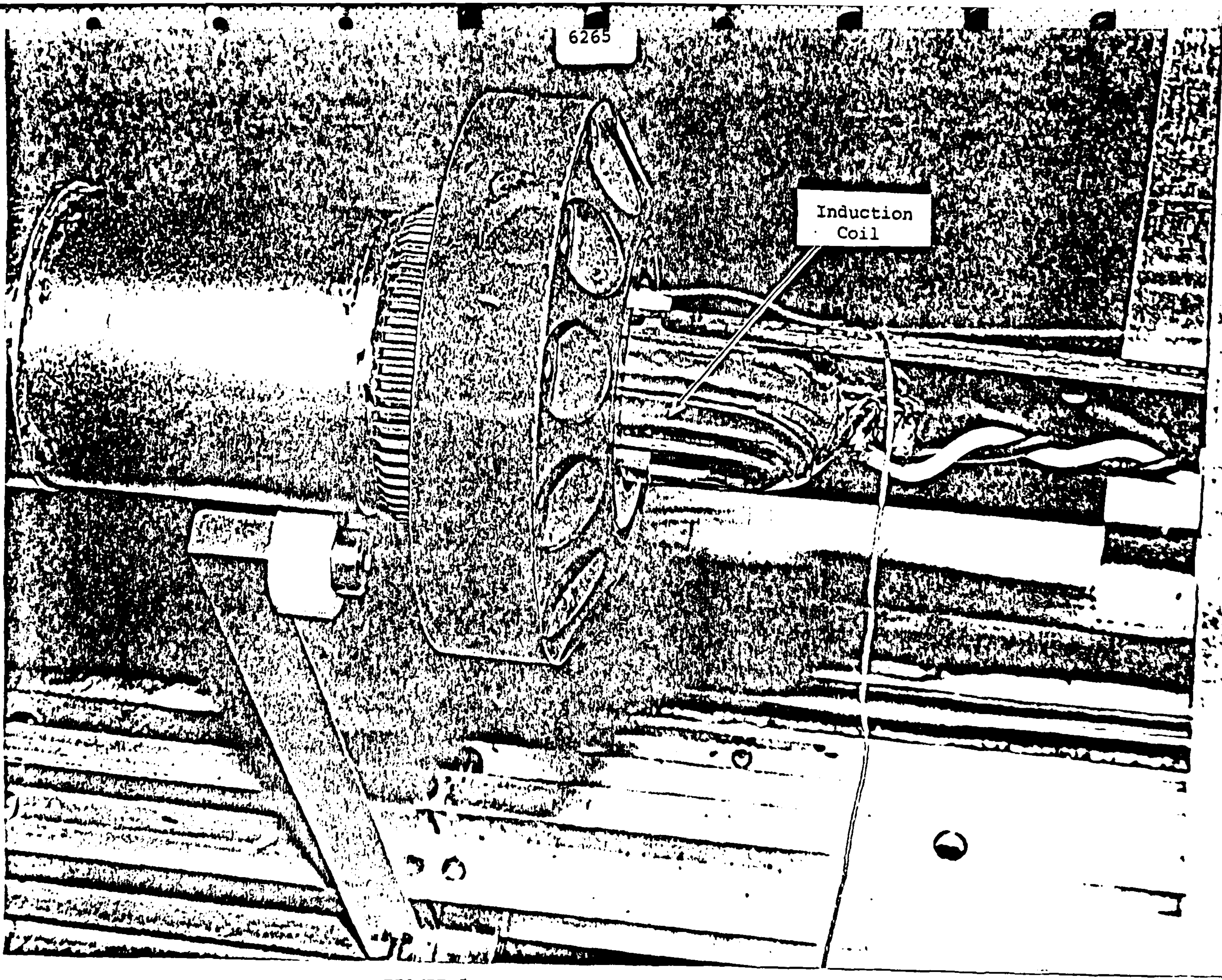


FIGURE 5. ECP PROBE IN SPINDLE BORE

III. EXPERIMENTAL RESULTS

A. ECP Probe on Crest of Threads

Initial ECP data were obtained on Spindle No. 1 which contained three air abrasive slots (designated A, B, C in Figure 2) spaced 120° apart around the circumference in the root of one thread. Excellent ECP signals were obtained from all three defects and the experimental results are shown in Figure 6. These data exhibit several important characteristics. First, the signal background is far above electronic noise and is highly repeatable for repeat scans. The ECP sensitivity is limited only by this coherent signal background obtained from the spindle itself and not by electronic noise. Second, signals are obtained not only when the probe passes directly over the slots in the same thread, but also when the probe is located over adjacent threads. Note that when the probe passes directly over each slot, the signal is first positive going and then negative going. However, when the probe is located over the adjacent thread on either side of the slot, the signal reverses polarity and is first negative going and then positive going. This relationship of ECP signal polarity with respect to probe position is characteristic of a typical ECP response and indicates that the ECP signals are responding as expected even in the presence of the complex geometry imposed by the spindle threads.

To determine sensitivity of the ECP method to smaller defects which more closely approximate the thumbnail shape of a fatigue crack, a series of EDM slots was machined in a thread root of Spindle No. 2. These defects are designated as E, F, G in Figure 3 with the smallest being slot G which is 0.021 in. long by 0.009 in. deep by 0.0025 in. wide. ECP data from these slots are shown in Figure 7. Note that distinct signals are obtained from all slots. Signals are evident in adjacent threads for the two larger slots; however, the small slot signal is not discernible above the signal background in adjacent threads. Again, the signal polarity reversal is evident from the signals in adjacent threads.

The two signals designated on the right side of the figure are from rough edges on the crest of one thread which were apparently due to damage during handling. The rough edges represent an abnormal thread condition which may be desireable to detect during inspection. Disregarding the signal from the rough thread, the signal-to-background ratio obtained from slot G (0.021 in. long by 0.009 in. deep) is 1.3 to 1.

In order to improve the signal-to-background ratio for the small defect, the cutoff frequency of the high-pass filter was set to a lower value to remove additional lower frequency background components from the signal. While the signal to background ratio is improved by this process, the signal shape is somewhat distorted as shown in Figure 8. For detection purposes only and not defect characterization (size, orientation, etc.), this distortion is not significant since it is only the signal level with respect to the signal background which is meaningful. By altering the filtering cutoff frequency, the signal-to-background ratio is increased to 2 to 1, disregarding the signal from the rough thread. Therefore, a defect on the order of 0.021 in. long by 0.009 in. deep is the minimum detectable with a signal-to-background ratio

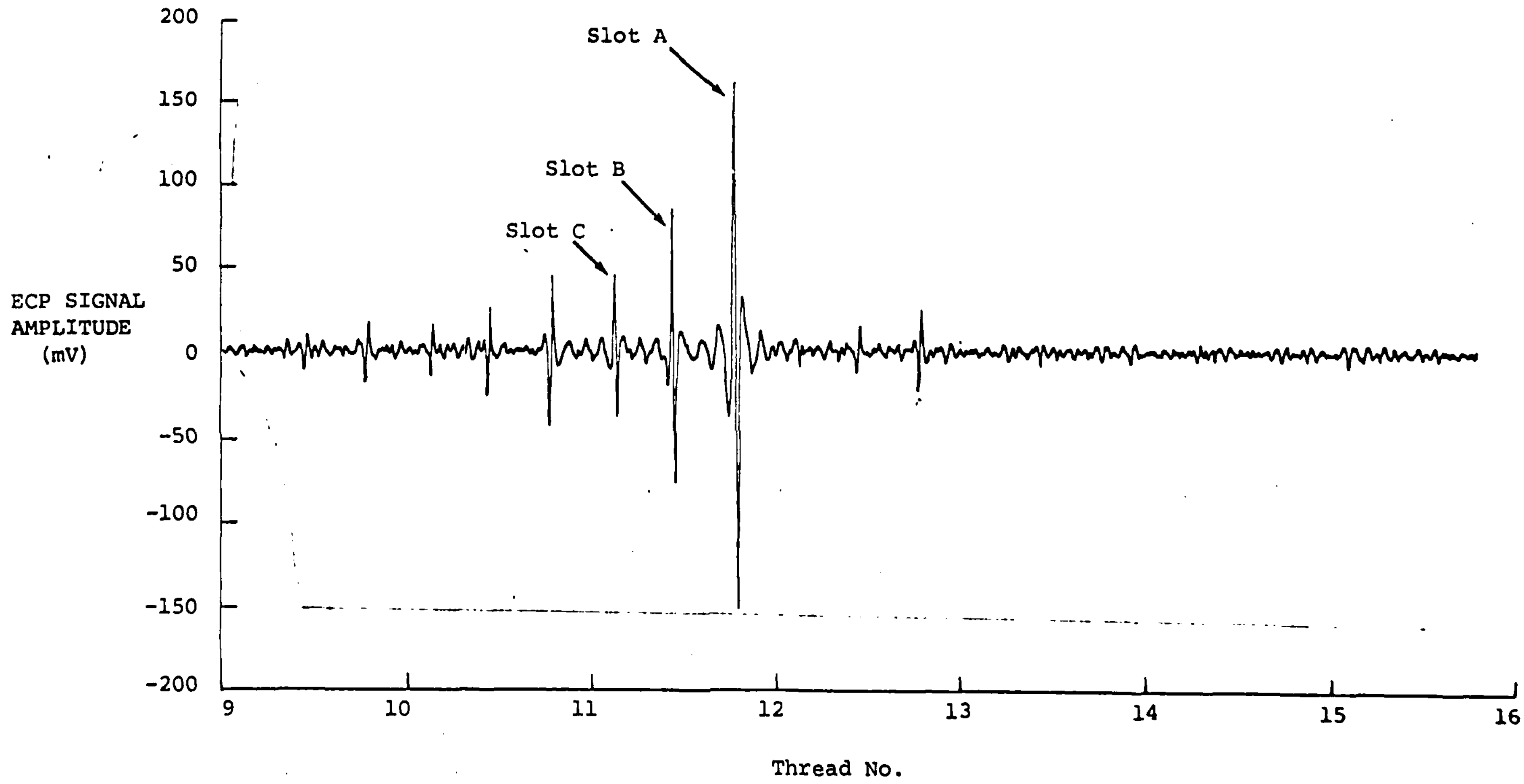


FIGURE 6. ECP SIGNALS FROM AIR ABRASIVE SLOTS IN SPINDLE NO. 1

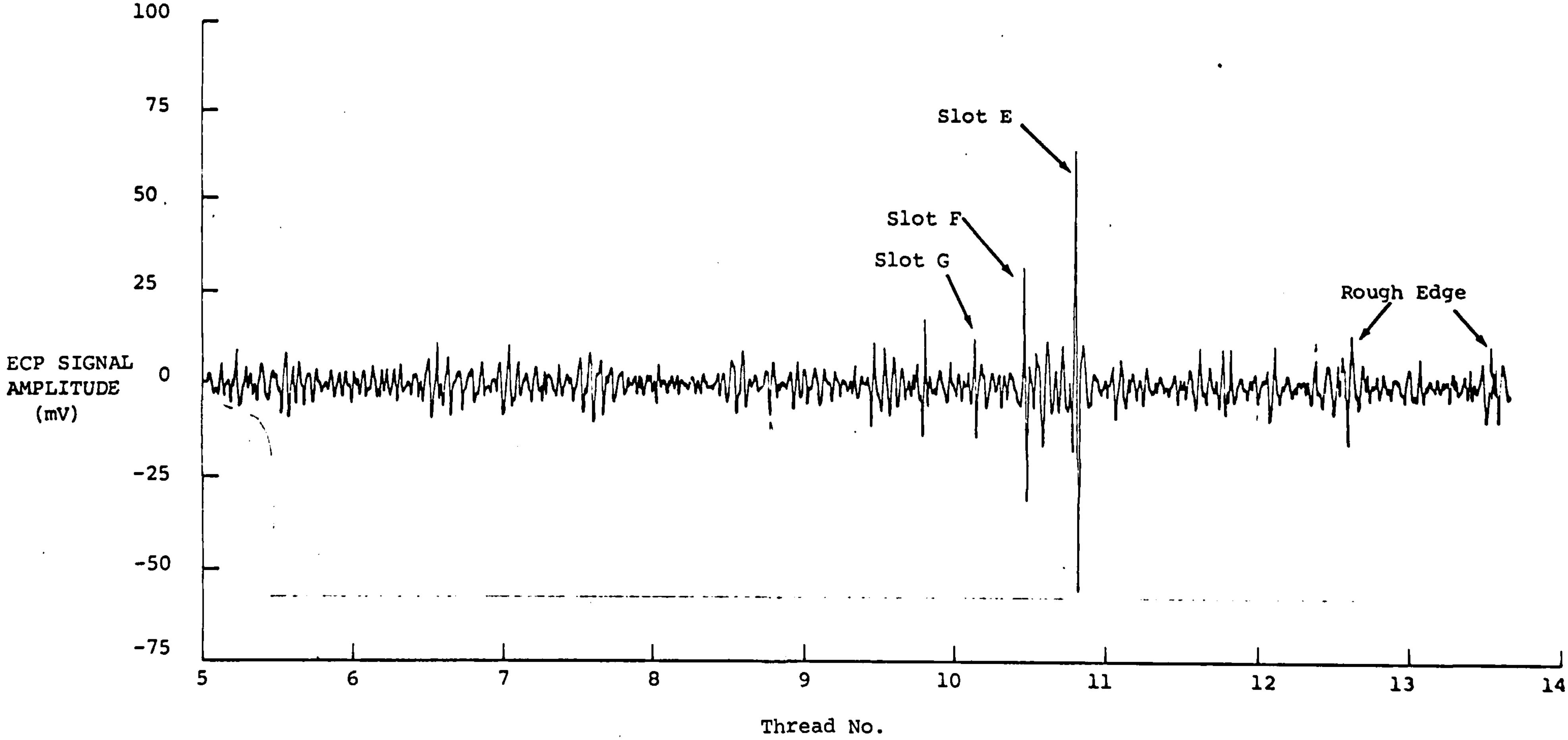


FIGURE 7. ECP SIGNALS FROM EDM SLOTS IN SPINDLE NO. 2

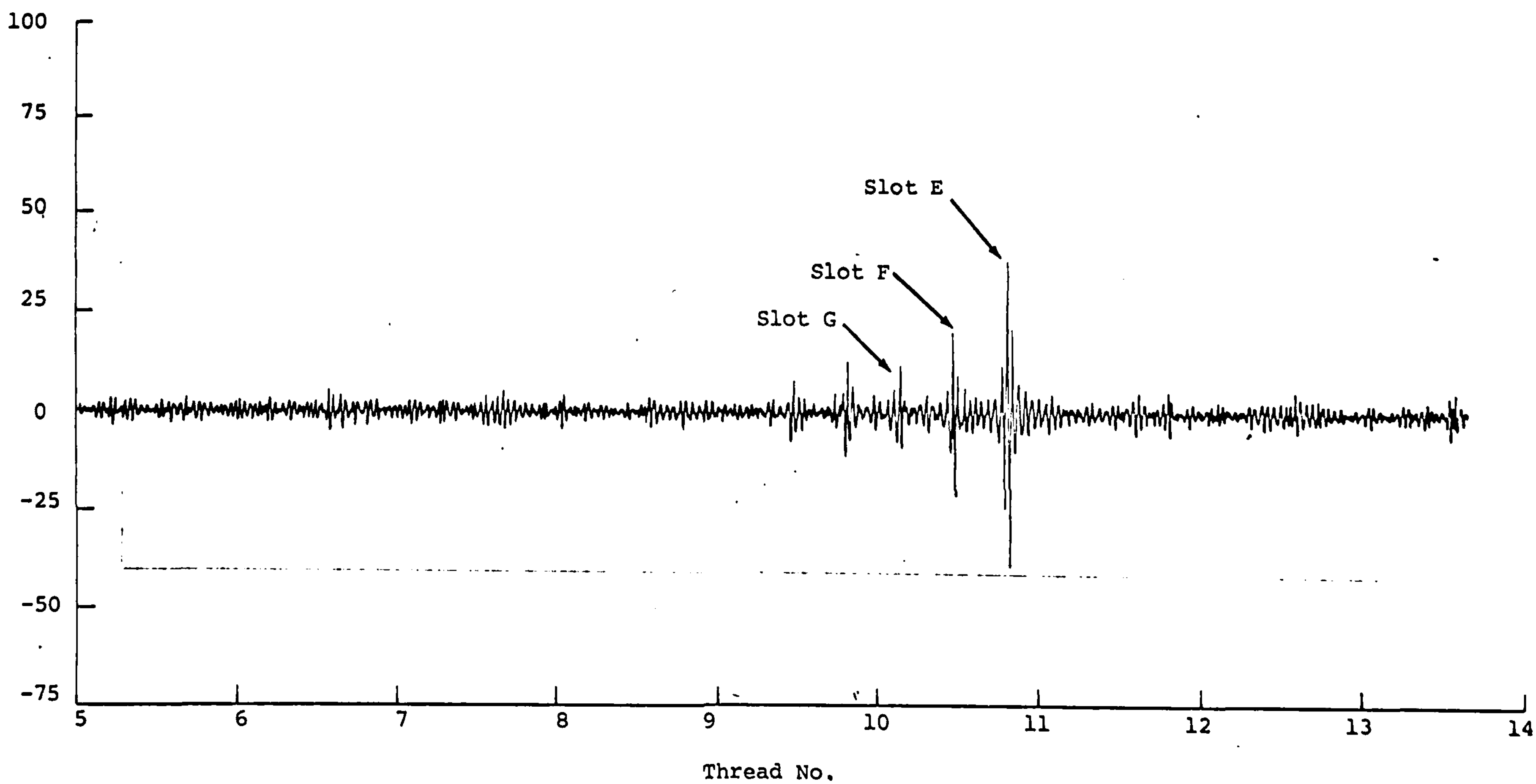


FIGURE 8. ECP SIGNALS FROM EDM SLOTS IN SPINDLE NO. 2 WITH ADDITIONAL LOW FREQUENCY COMPONENTS REMOVED

considered acceptable for reliable detection using the filtering approach employed here. It is anticipated that with more sophisticated signal processing, even smaller defects could be detected.

B. ECP Probe in Spindle Bore

Initial data were obtained from defect D (0.60 in. long by 0.110 in. deep) in the fourth thread of Spindle No. 1. The experimental data are shown in Figure 9 beginning one revolution before the first thread is reached (designated thread 0) through the sixth thread. It is quite evident that a substantial signal is obtained from this defect not only when the probe passes directly under the defect but for a significant number of revolutions on either side. Although the signal reverses polarity as was the case with the small defects on the crest of the threads, this polarity reversal occurs outside the region shown in the plot because the signal is significantly more spread out due to penetration of the electromagnetic field through the spindle wall thickness.

In order to determine the smallest detectable defect size with the ECP method, slot H (0.195 in. long by 0.060 in. deep) was machined in the first thread of Spindle No. 2. This defect was not detected above the signal background. Subsequently, slot I measuring 0.305 in. long by 0.087 in. deep was then machined 180° from slot H and the ECP signals from this slot are shown in Figure 10. The signal-to-background ratio obtained from this defect is 2.1 to 1. Therefore, defects of this size are detectable with the probe positioned in the spindle bore without removal of the spindle from the helicopter. Again, detection of smaller defects would be possible with more sophisticated signal processing.

The signal-to-background ratio achieved for defect I is obtainable only for defects present in threads 1 through 6 (from the spline) since for higher thread numbers the ECP probe moves closer to the end of the spindle and signal background level is increased due to current perturbations from the end of the spindle. It is anticipated, however, that only the first few threads would require inspection since these threads carry the highest loads and cracks will initiate there first.

C. Equivalence of Slots and Fatigue Cracks

Although machined slots are commonly used to simulate fatigue cracks in NDE investigations, one must be confident of the relationship between signals from slots and those from actual fatigue cracks when using slot data to estimate the sizes of fatigue cracks which can be detected. In this regard, a distinct advantage of the ECP method is the independence of the signal on crack opening for fatigue cracks and the characteristic linear relationship obtained between ECP signal amplitude and crack/slot interfacial area.

In prior work,[2] a fatigue crack was grown to various lengths (up to 0.050 in. surface length) in a smooth Ti 6-4 rod type tensile specimen in a laboratory fatigue machine under stress conditions which produced a true half-penny shaped crack with a 2:1 aspect ratio. Signals from this fatigue crack when it was 0.040 in. long and 0.020 in. deep are shown in Figure 11. The difference between the crack signal and the slot signals obtained from the spindle in this project is a result of the different scan direction taken on the spindle threads, but this does not affect the peak amplitude response.

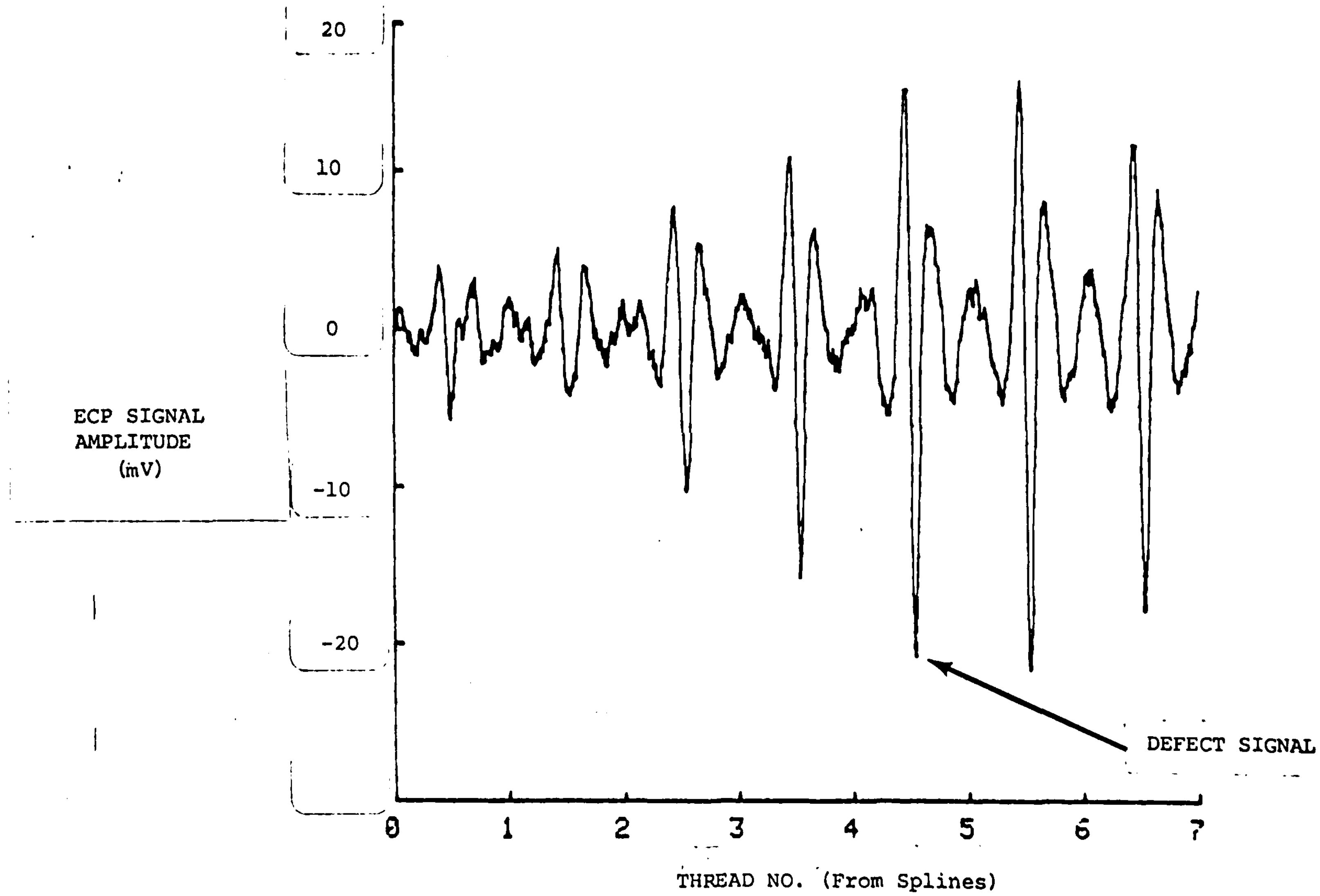


FIGURE 9. ECP SIGNALS FROM DEFECT D (0.60 IN. L. X 0.110 IN. D.)
IN SPINDLE NO. 1 WITH PROBE IN BORE

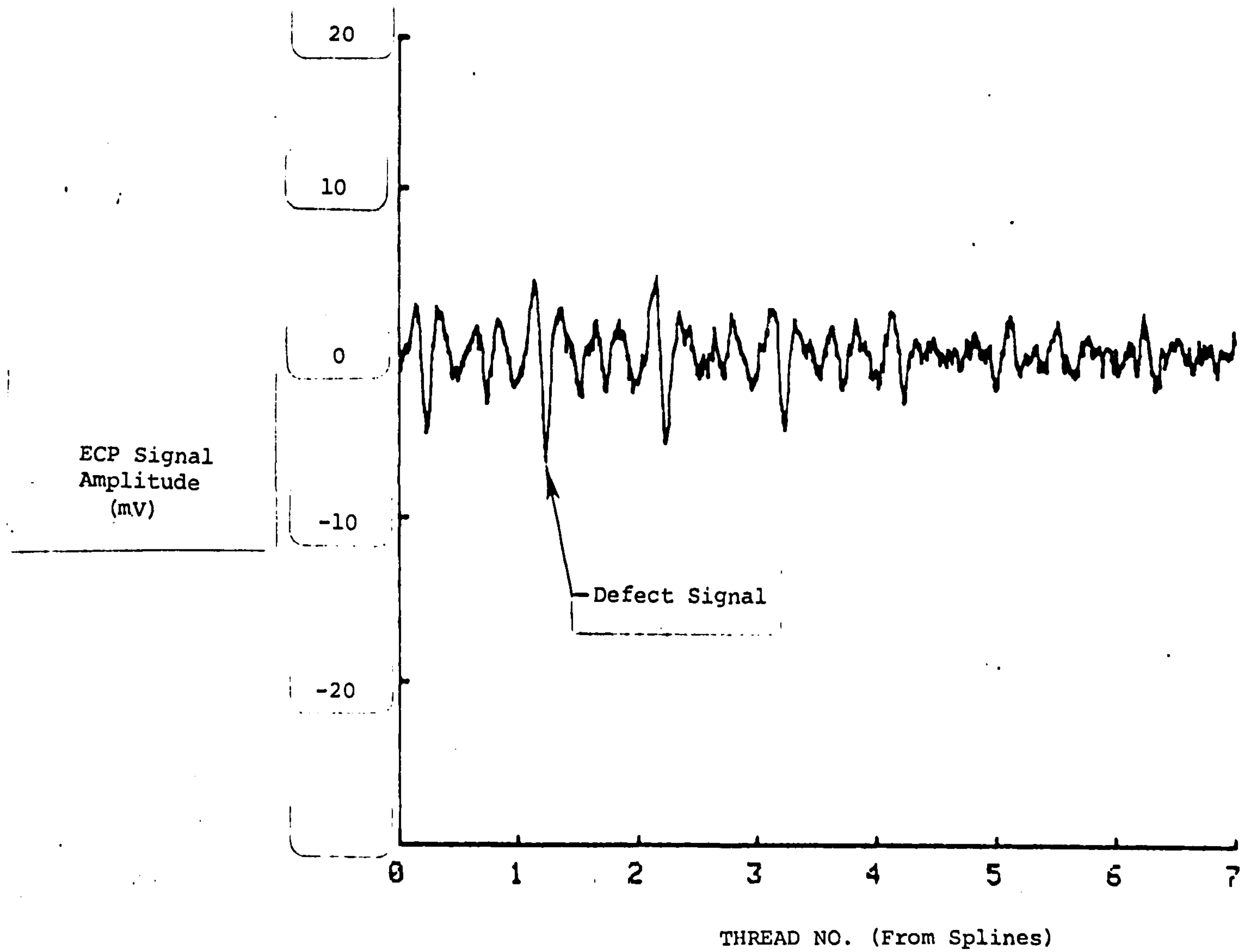
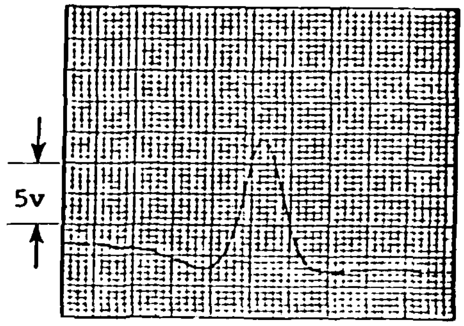
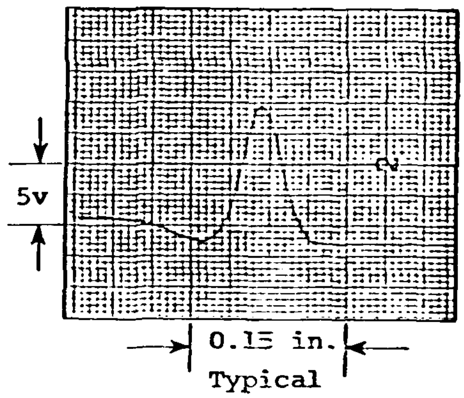


FIGURE 10. ECP SIGNALS FROM DEFECT I (0.305 IN. L. X 0.087 IN. D.) IN SPINDLE NO. 2 WITH PROBE IN BORE



a. No Load



b. Full Load

FIGURE 11. ECP SIGNALS FROM 0.040 IN. L. X 0.020 IN. D. FATIGUE CRACK IN TITANIUM ROD SPECIMEN WITH AND WITHOUT LOAD

Two conditions of crack closure were evaluated. In the first case, the ECP signal was obtained under no load conditions where the crack is tightly closed. In the second case, the signal was obtained using a load equivalent to the peak cyclic load to completely open the crack, thus producing a defect equivalent to a slot with a finite opening. Essentially no change in signal amplitude was observed.

ECP data for the fatigue crack plotted as a function of interfacial area of the crack are shown in Figure 12. Similar data for the machined slots scanned with the probe on the crest of the spindle threads are shown in Figure 13. (Since the crack data were obtained using a different instrumentation system than with the spindle, the absolute values of signal amplitude are different for the two cases.) The slot data are from both rectangular air abrasive slots with widths of approximately 0.007 in. and from thumbnail shaped EDM slots with widths of approximately 0.0025 in. Note that the slots which have different widths produce no apparent influence on the signal response as was the case for the fatigue crack with different crack opening displacements. For both types of slots and the crack an excellent linear relationship is obtained (within experimental error) showing that the interfacial area determines the ECP response not the shape or width of the slot or crack. This linear relationship as well as independence of signal on crack opening are also predicted by a theoretical model under development at SwRI.

Based on the independence of the fatigue crack data on the opening of the crack and the linear relationships obtained for cracks and slots as a function of interfacial area, it is concluded that fatigue cracks and slots of equivalent interfacial area produce essentially equivalent ECP responses.

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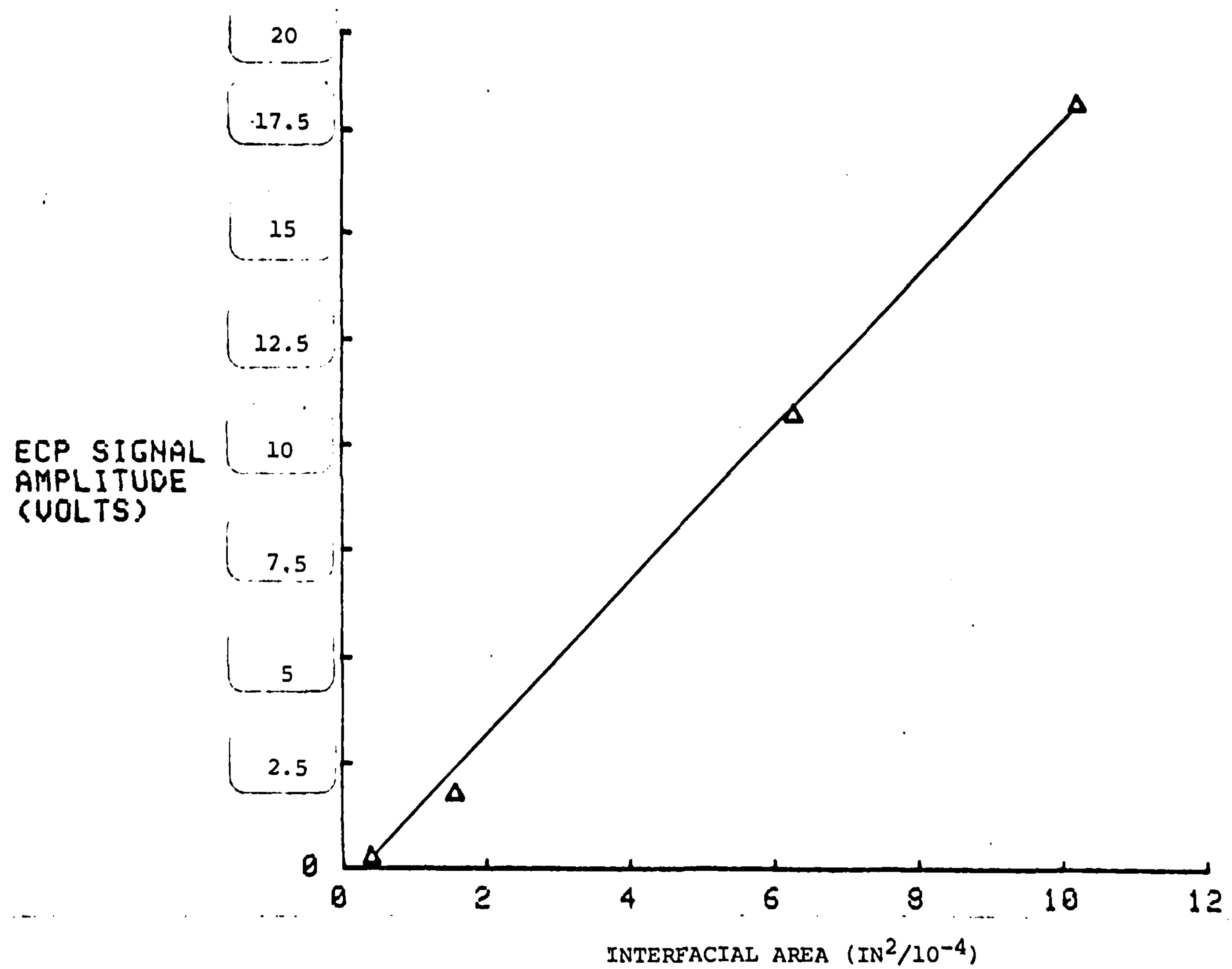

FIGURE 12. ECP SIGNAL AMPLITUDE VS. INTERFACIAL AREA FOR CRACK IN TITANIUM ROD SPECIMEN

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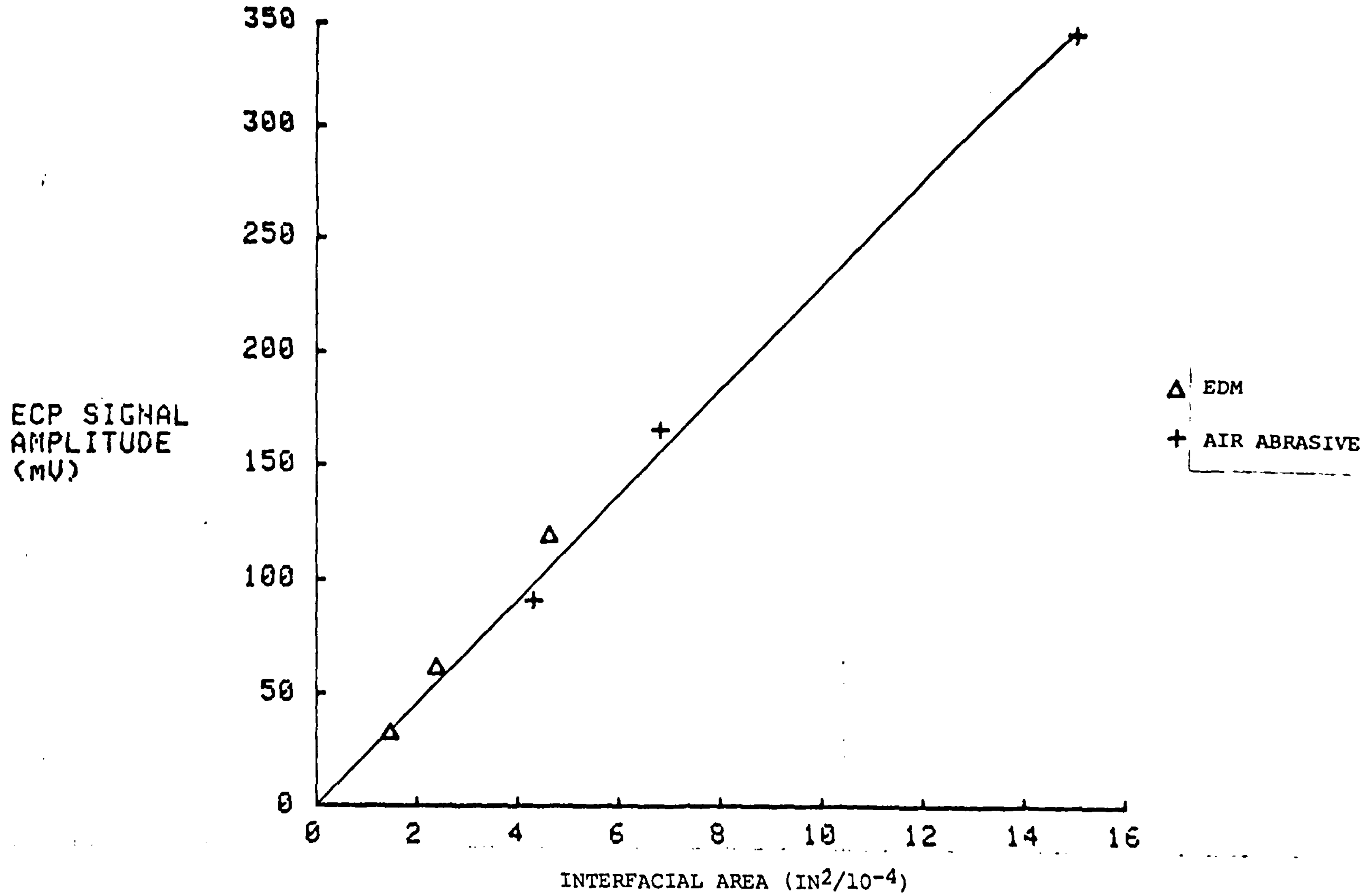

FIGURE 13. ECP SIGNAL AMPLITUDE VS. INTERFACIAL AREA FOR AIR ABRASIVE AND EDM SLOTS IN TITANIUM SPINDLES

IV. ECP INSPECTION SYSTEM CONCEPTUAL DESIGN

A. ECP Probe on Crest of Threads

A conceptual design of a proposed depot ECP spindle thread inspection system for spindles removed from the helicopter is shown in Figure 14. This system would incorporate a probe which rides on the crest of the threads for detection of small defects in the thread roots. The probe mechanism would be enclosed and the probe would ride on an air bearing on the spindle threads to reduce wear and noise due to direct rubbing of the probe on the spindle threads. The system would be designed for use by operators with a minimum of special training. The operator would position the spindle on the support rollers and insert it into the enclosed probe mechanism. He would engage the spindle threads in a nut incorporated in the enclosed mechanism and rotate the spindle until the ready light was activated. At this point, the scan button would be depressed and the ECP probe would begin a helical scan for inspection of all threads. Note that the probe would be rotated and not the spindle. If a defect indication was obtained, both an audible alarm and an indicator lamp would be activated to alert the operator and inspection would be halted. At this point, the strip chart recorder would be engaged by the operator to provide a permanent record of the defect signals. One strip chart channel would provide index marks for locating the defects in the spindle. Upon completion of the inspection, the operator would rotate the spindle to disengage the threads and remove it from the probe mechanism.

B. ECP Probe Inside Spindle Bore

A conceptual design for an ECP inspection system to be used with the spindle in place on the helicopter is shown in Figure 15. This inspection will require that the rotary wing either be removed from the helicopter or swung aside on one attachment pin to provide access to the spindle bore. The ECP probe would be completely enclosed in a housing on a remote inspection head which would be inserted into the spindle and locked into place with a retractable locking pin inserted into one rotary wing attachment hole. Since the probe is totally enclosed, it would be immune to contamination from dirt, moisture, etc. thus providing a very rugged, low maintenance system. The ECP probe would rotate in a helical fashion inside the enclosed head to provide inspection of the first seven spindle threads.

The remote inspection head would be connected to a portable control unit and the operator would initiate the inspection process by depressing a button on the control panel. Any defect indications would be provided by both audible and visual alarms. Upon detection of a defect, the inspection process would be halted and the operator would then engage the strip chart recorder to provide a permanent record of defect indications. One channel of the strip chart would be devoted to index markers which would provide a means for locating the defects in the spindle. Upon completion of the inspection, the operator would disengage the retractable locking pin and remove the remote inspection head from the spindle.

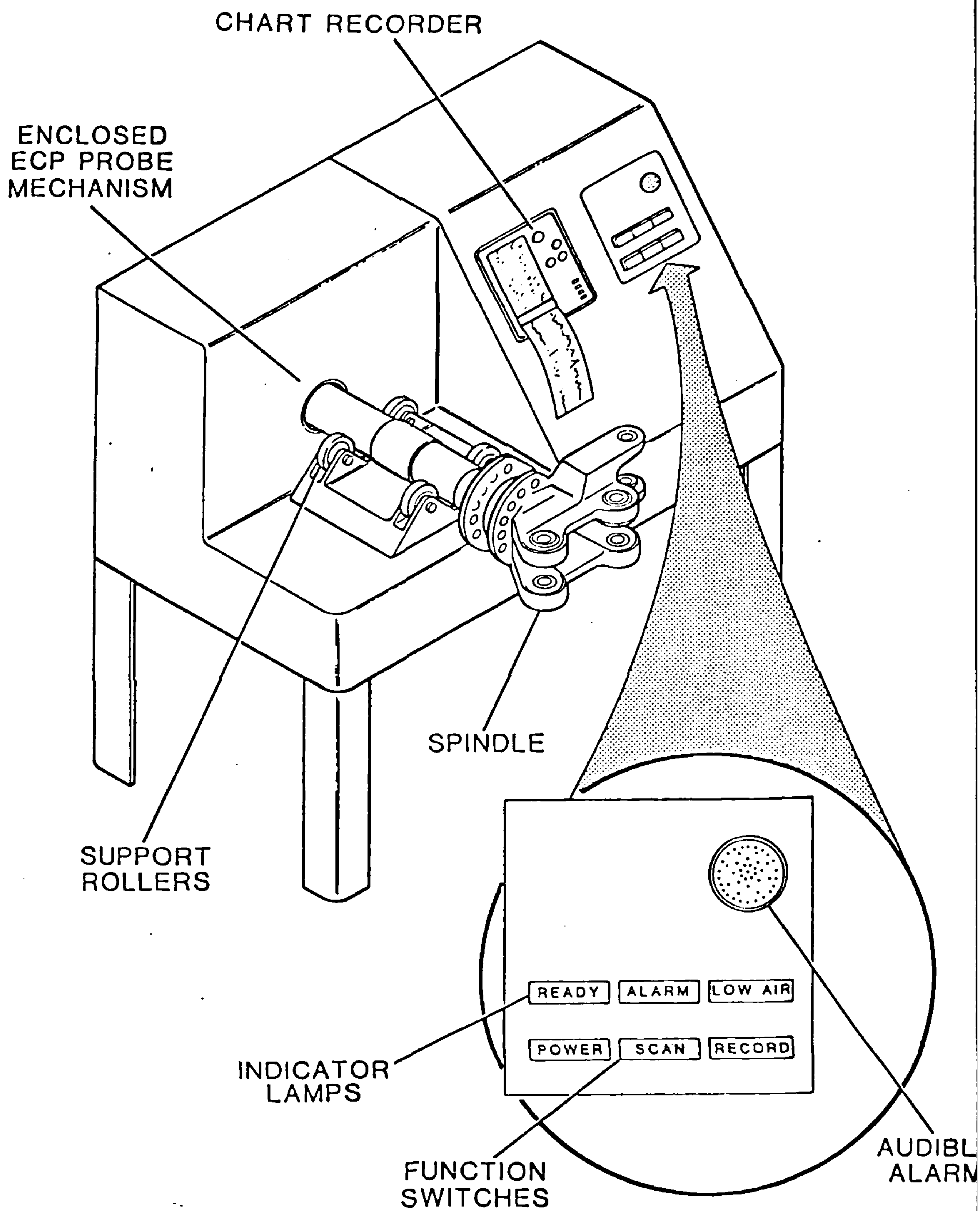

FIGURE 14. CONCEPTUAL DESIGN OF ECP INSPECTION SYSTEM WITH SPINDLE REMOVED FROM HELICOPTER

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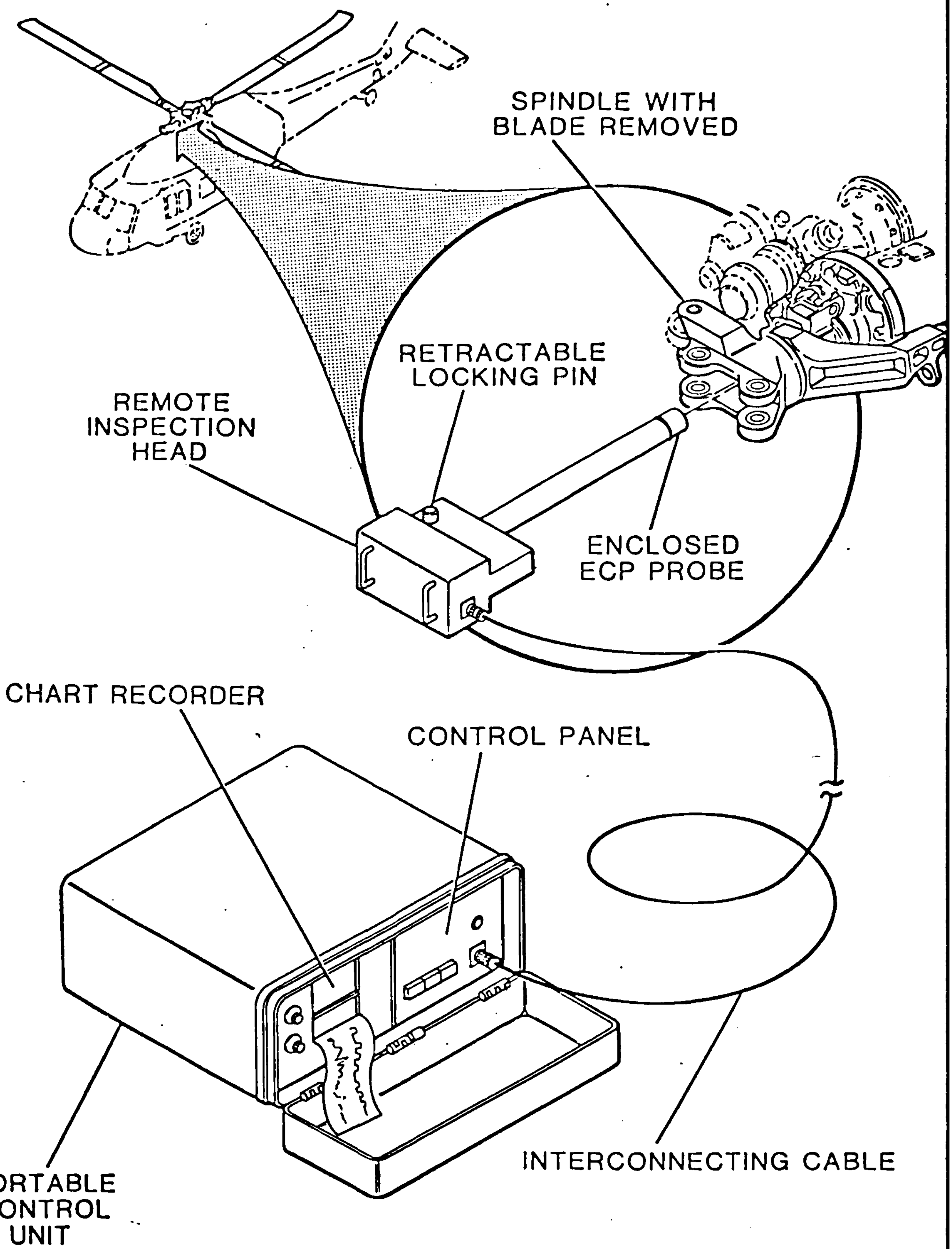

FIGURE 15. CONCEPTUAL DESIGN OF ECP INSPECTION SYSTEM WITH SPINDLE IN PLACE ON HELICOPTER

V. CONCLUSIONS AND RECOMMENDATIONS

The ECP method was shown to be capable of inspecting the Black Hawk helicopter rotary wing-head spindle threads for fatigue cracks in the thread roots. The ECP method is applicable in two inspection configurations. For detection of very small fatigue cracks, the spindle would be removed from the helicopter and the probe scanned on the crest of the threads. This method was shown to be capable of detecting simulated fatigue cracks measuring 0.021 in. long by 0.009 in. deep by 0.0025 in. wide. For safety-of-flight inspection with the spindle still in place on the helicopter, the ECP method was shown to be feasible for detecting fatigue cracks in the thread roots by inserting a probe into the spindle bore and inspecting through the spindle wall thickness. With this arrangement, detection of simulated fatigue cracks as small as 0.305 in. long by 0.087 in. deep by 0.004 in. wide was successfully demonstrated. It is anticipated that with additional signal processing methods, detection of even smaller defects could be realized.

It is recommended that ECP inspection systems be developed according to the conceptual designs presented in the report. Inspection with the probe positioned on the crest of the threads could be realized by a depot level system designed for detection of very small fatigue cracks. It is anticipated that spindles with small cracks could be reworked using a blending operation to remove the cracks and then be placed back into service. For safety-of-flight inspections, a system could be developed for inspecting the spindle without removing it from the helicopter.

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